Validation of a Computational Fluid Dynamics Model of Axial Jet Mixing for Cryogenic Propellant Tank Pressure Control

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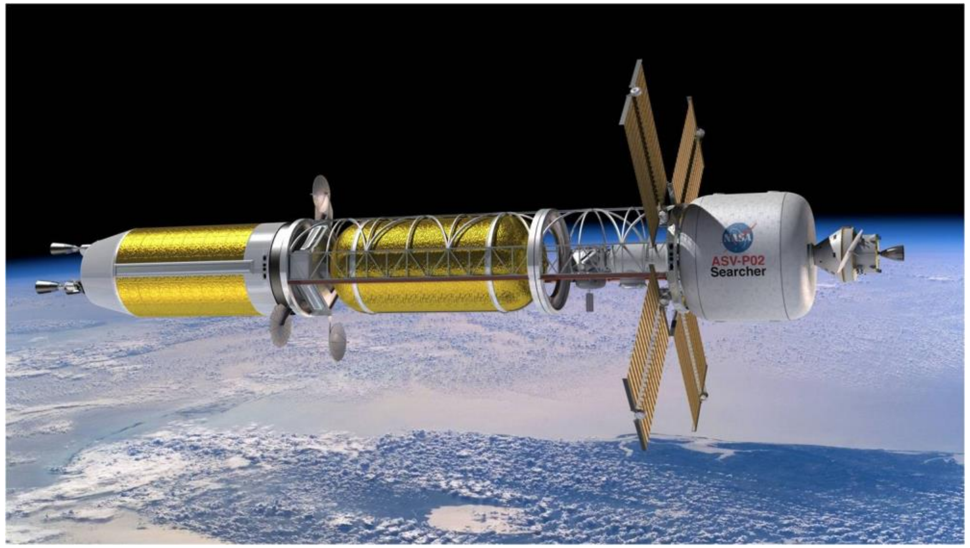
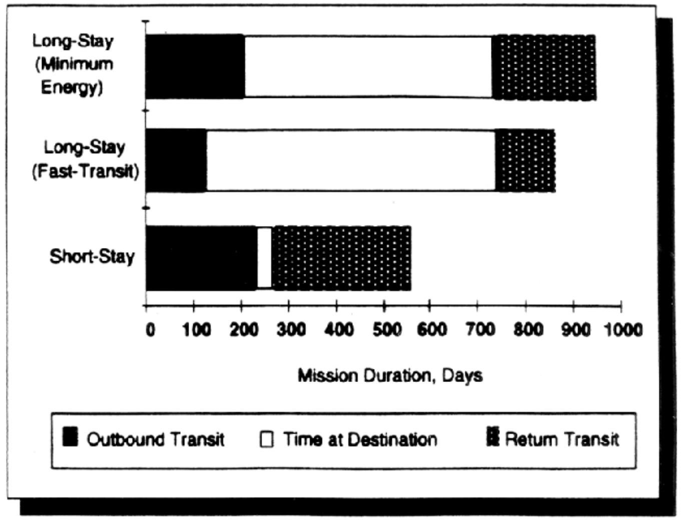
Background

- The Fluid Dynamics Branch at the NASA Marshall Space Flight Center (MSFC) is preparing to support flight programs through analysis of a variety of cryogenic fluid management (CFM) applications.
- Many vehicles being considered for future manned missions to the moon and beyond use chemical or nuclear thermal propulsion systems that rely on cryogenic propellants.
- Storing cryogenic propellants for later use is a challenge, though.
- Many areas of active CFM research, testing, and design involve propellant conditioning to ensure propellant remains a usable liquid for propulsion.
- Multiple technologies may be used to achieve adequate conditioning including the subject of this work, a jet-based mixer.
- Mixing serves to homogenize fluid temperatures and decrease ullage pressure.
- Development and validation of a modeling methodology for jet-based mixing, shown herein, was conducted to prepare for in-line design work.

NTP Concept – NASA





Test Description

- Jet mixer testing of a liquid hydrogen (LH2) tank was performed at the NASA Glenn K-Site facility [1]
- Tank heat leak was measured to be 4.2 W/m^2 [2,3]
- Test article was nearly ellipsoidal with a 2.2 m major diameter and 1.2 major-to-minor diameter ratio
- Axial jet mixer had a 0.0221 m exit diameter with an exit plane 0.51 m from the tank bottom
- Pre-test operations included:
  - Hardware thermal conditioning
  - Draining to target fill level
  - Pressurization to target pressure
- Data from two tests in the series were used for validation, see table below
  - Self-pressurization method
  - No non-condensable gas present

Test Case	Fill Level by Volume (% of Total)	Jet Flow Rate (m^3/hr)	Initial Ullage Pressure (MPa)
434	86.3%	3.47	0.1861
436	85.3%	1.82	0.1870

Test Article Configuration [1]

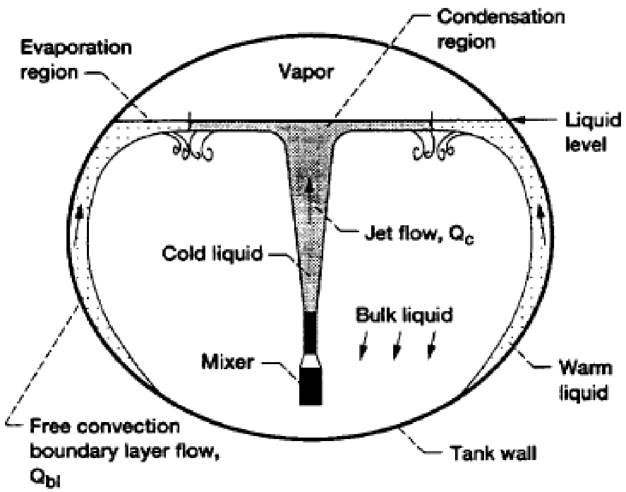


Figure 1.—The flow pattern and phenomena of a mixing tank.

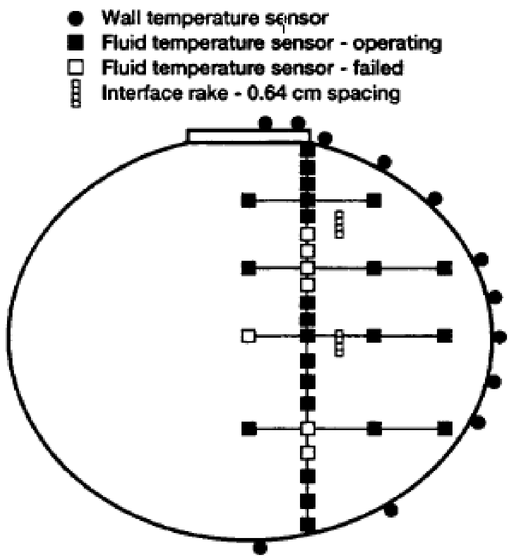


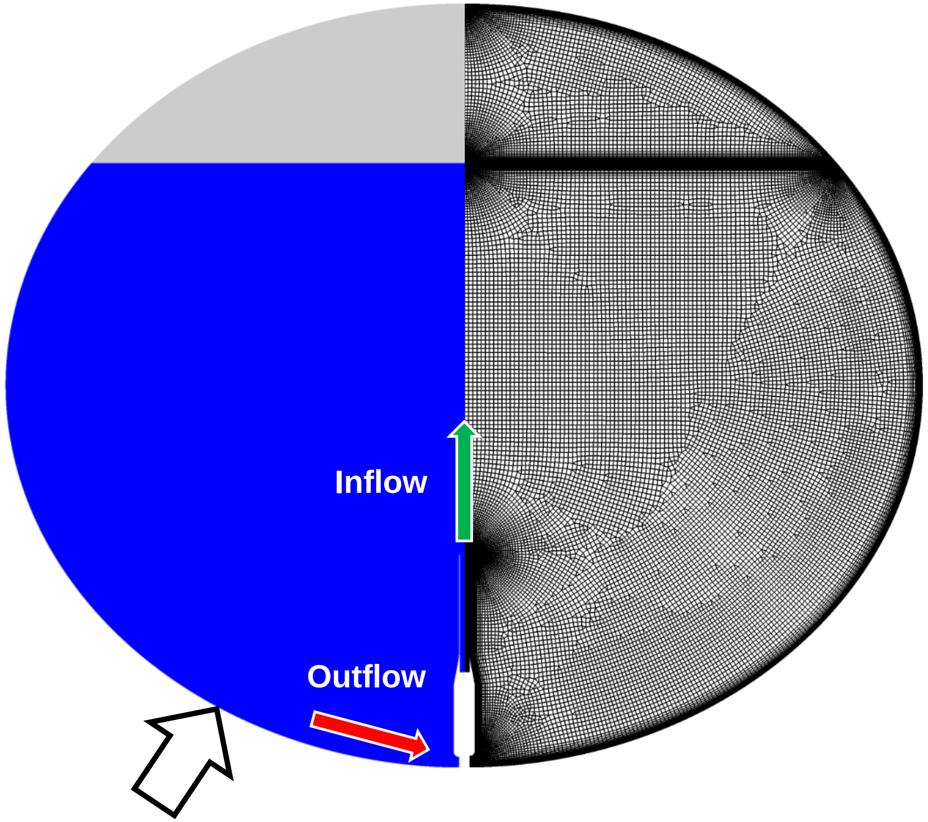
Figure 2.—Tank instrumentation.

Simulation Methodology

- Used Loci/STREAM-VoF for every simulation
  - Pressure based Navier-Stokes solver
  - Sharp interface method of distinct phase representation [4,5]
  - Rigid interface boundary condition allowing heat and mass transfer
  - Interface normal velocity was zeroed while shear flow was allowed
  - 2^{nd} order accuracy in space and 1^{st} order accuracy in time
- Modeled a 2D axisymmetric version of the test article geometry
  - Modeled the mixer aft of the exit plane based on available photos
  - ~62 thousand unstructured volume cells for the nominal mesh
- Used a constant standard Earth gravity (9.81 m/s^2)
- Modeled incompressible LH2 and ideal GH2
  - Initial ullage pressure and temperature distribution was matched to test data
  - Liquid properties corresponded to 20.94 K and 0.184674 MPa [6]
  - Saturation conditions were calculated using the Antoine equation [6]
  - Used the Boussinesq approximation to model buoyancy in the liquid phase only
- Used an implicit kinetics-based phase change model [5]
  - Evaporation and condensation at gas-liquid interfaces
  - Accommodation coefficient of 0.001 for nominal simulations
- Used the improved 2003 Shear Stress Transport model (SST) [7] for turbulence modeling
  - Specified low initial turbulence quantities
  - Enforced a wall treatment at the gas-liquid interface in lieu of damping [8,9]

Model Geometry

(Left: Liquid fill level shown in blue / Right: Nominal mesh)



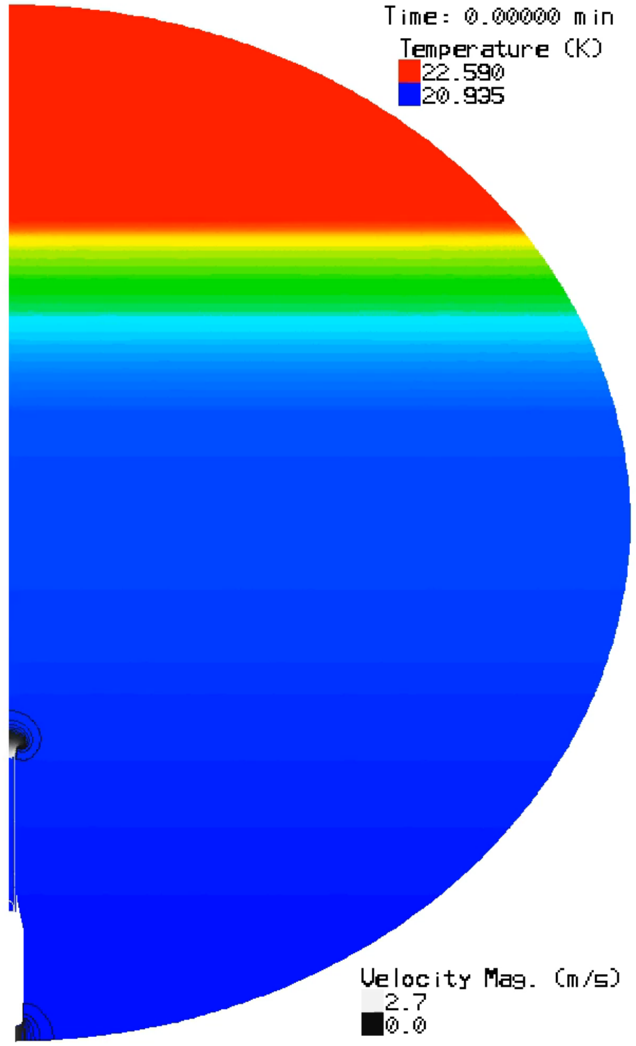
Uniformly distributed 4.2 W/m^2 heat flux applied to tank walls

Jet Mixing Dynamics

- An animation of the temperature field for the simulated high flow rate test case is shown with superimposed velocity magnitude contour lines.
  - Both the maximum temperature and velocity magnitude contours are limited to better show dynamics within the bulk liquid.
- These results are for the nominal mesh and sensitivity parameter settings but were typical of every simulation described herein.
- Initial liquid temperature stratification developed during self-pressurization is destroyed through jet mixing.
  - Self-pressurization was not explicitly modeled in the presented analysis results
  - However, it was shown that the natural convection velocity field had a negligible effect on the pressure transient due to the overwhelming jet velocity
- The primary mechanism of pressure control is the reduction in gas-liquid interface temperature through mixing, as expected.
  - Reduced interface temperature prompts vapor condensation.

Case 434

High Flow Rate



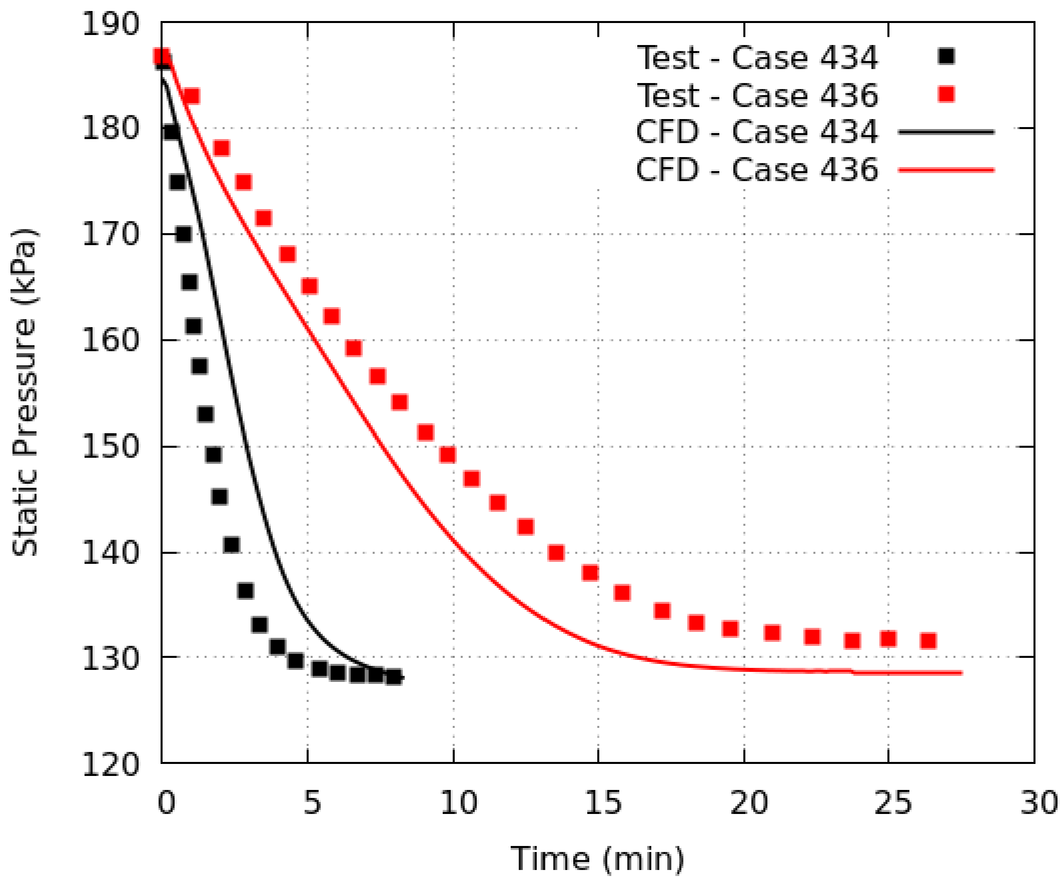
Jet Flow Rate Sensitivity

- Pressure transients for both considered tests are shown in the figure along with nominal simulation results.

- Mixing at a lower flow rate consequently reduced the pressure drop rate, as expected.

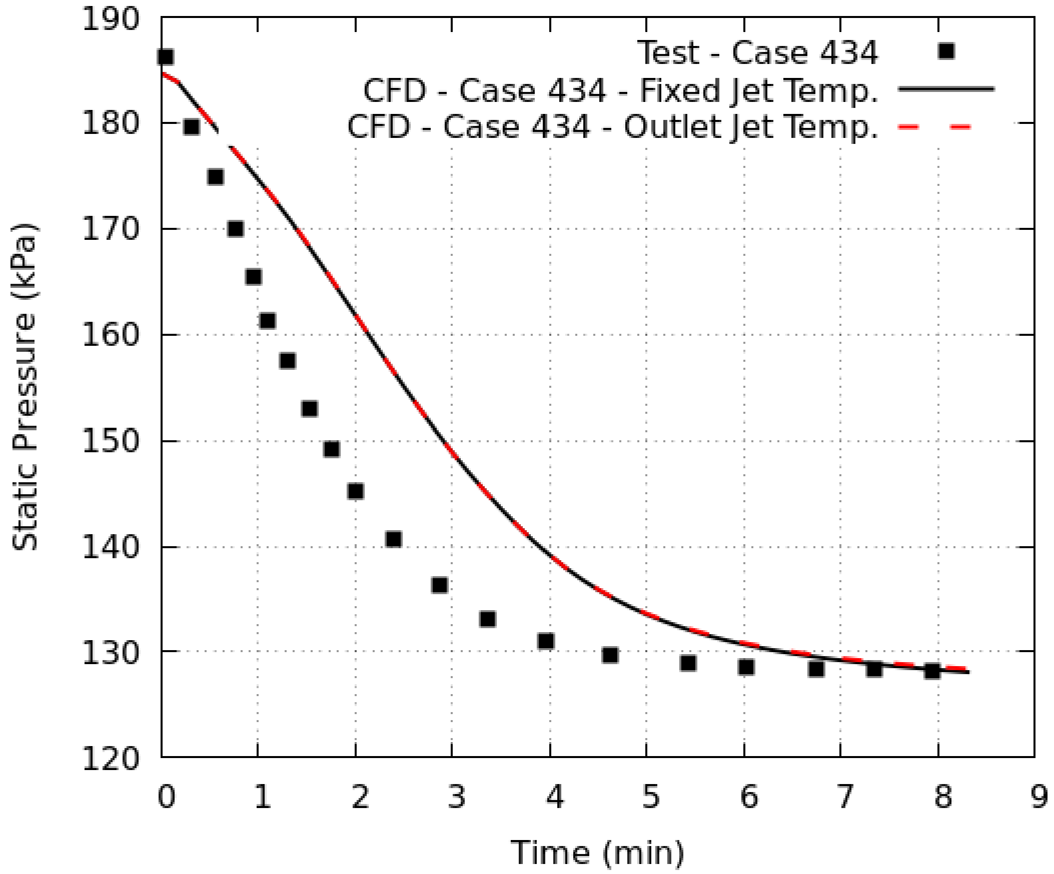
- The analysis results match the pressure drop trend, magnitude, and timing well but with notable deviation.

- Of particular note, the final pressure for the low flow rate case, 436, differs between experimental measurement and analysis result.
  - The analysis predicted a final gas-liquid interface temperature below that of the experiment resulting in the lower pressure, although the temperature difference is less than 0.1 K.



Jet Temperature Sensitivity

- Jet temperature was fixed for nominal simulations to the initial temperature near the mixer intake.
- A subsequent simulation was conducted where jet temperature was updated throughout the simulation to the mixer intake temperature.
- Effects of this change were minor as can be observed at right
- It is apparent that mixing did not significantly alter the liquid temperature at the bottom of the tank for the simulated conditions.
- It is possible that proper modeling of jet temperature is more impactful for different conditions, like higher mixing rates or longer duration mixing at lower flow rates, so the capability will be used in future support of this application.



Phase Change Model Sensitivity

- The phase change model contains a coefficient which acts as a limiter on mass transferred in a time step (α).
  - The Hertz Knudsen model used is shown below.

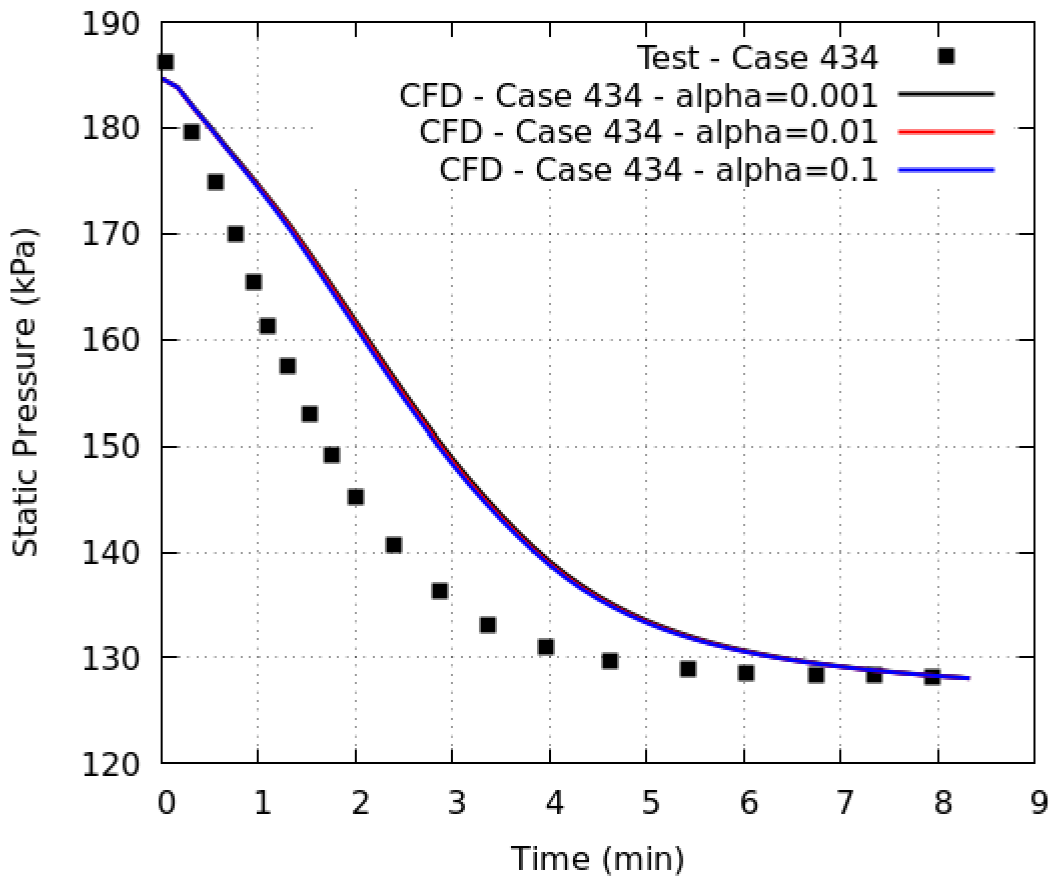
$$\dot{m} = \alpha \left(\frac{M}{2\pi RT}\right)^{1/2} (P_i - P_v)$$

- A value of 0 would inhibit mass transfer while a value of 1 would allow for a maximum amount of mass transfer.

- Numerical stability issues can arise from using too high of a phase change coefficient, so values between 0 and 1 are commonly used.

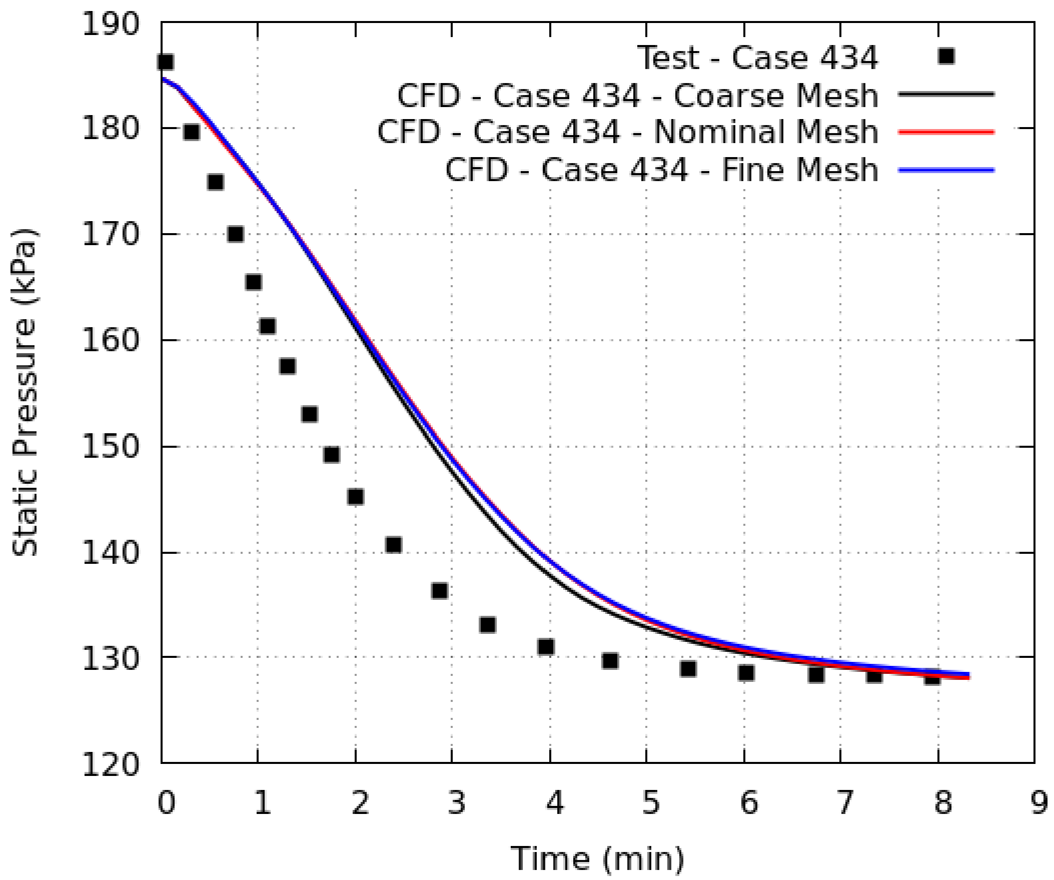
- Results show convergence of the phase change coefficient by at least the nominal phase change coefficient value, 0.001, given the nominal mesh resolution and time step.

- Future simulations of jet mixing will target relaxing spatial resolution of boundaries necessitating additional phase change coefficient sensitivity studies.



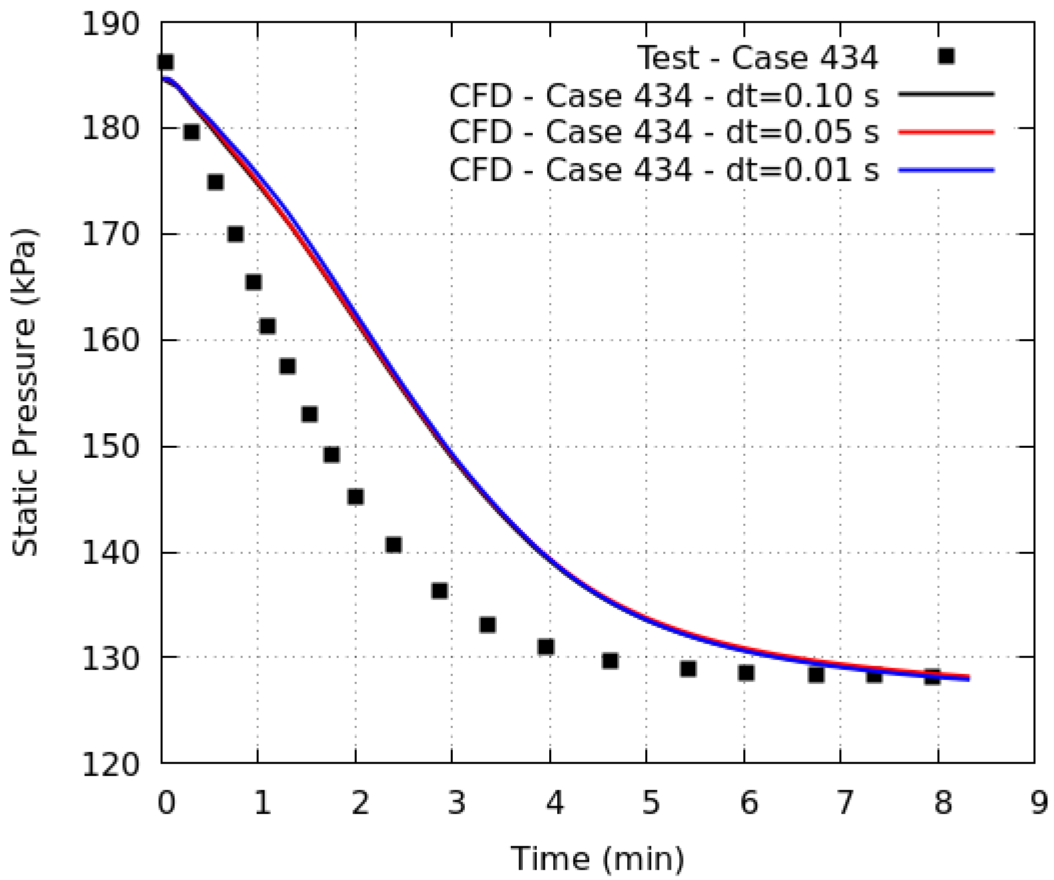
Spatial Resolution Sensitivity

- Sensitivity of the pressure transient to nominal cell edge length is shown at right
- Only a minor difference exists between the coarse mesh and more refined meshes which is likely due to capture of jet expansion or turning at the gas-liquid interface, as the normal spacing at the interface is constant among these meshes.
- Convergence was clearly reached for nominal cell edge lengths.
- Additional assessment of other mesh features like boundary layer spacing will be studied in the future since it is driving mesh size and will have a profound impact on support of any related in-line work.
  - All meshes used y+ < 1 on tank walls and interface



Temporal Resolution Sensitivity

- Results of the time step sensitivity study are shown at right
- Little variation was observed up to the nominal time step of 0.1 s.
- This result is unsurprising since RANS models smooth spatial and temporal fluctuations relaxing resolution requirements compared to other methods that more explicitly resolve turbulence.
- Additionally, the phase change model was already shown to be converged at the nominal time step.
- The time step achievable in this study is enabling of future in-line work, where long duration simulations can be computationally prohibitive for practical applications and offers room for additional model complexity that is sure to be added with flight-like designs of tanks and mixers.



Conclusion

- CFD simulations of axial jet mixing were conducted to develop and validate a modeling methodology in preparation for similar in-line design work.

- The nominal modeling methodology resulted in reasonable representation of the pressure drop trend, magnitude, and timing.

- There was little variation in the RANS model solutions for axial jet mixing across the multiple sensitivity parameters and spaces investigated.

- As such, a capability exists, at least within the analyzed parameter space, to make predictions of mixing flow rate and duration demands that inform a concept of operations and power budget.

Forward Work

- Future study will include expanded sensitivity ranges to identify the limits of each modeling parameter.
  - Preliminary results at lower fill levels show good agreement with experimental data.

- Turbulence modeling features like imposed damping on the gas-liquid interface will be implemented.

- Finally, features of the sharp interface method used within this study will be incorporated into the Loci/STREAM volume of fluid (VoF) method and validated.
- Having a capable VoF method for prediction of jet-based mixing will enable simulation of axial jet flow rates that significantly perturb the liquid interface, a scenario that may be preferential or unavoidable if in-space or at reduced gravity.

References

1. Lin, C.S., Hasan, M.M., and Van Dresar, N.T., “Experimental Investigation of Jet-Induced Mixing of a Large Liquid Hydrogen Storage Tank,” 6th Joint Thermophysics and Heat Transfer Conference, AIAA-94-2079, June 1994.
2. Stochl, R.J. and Knoll, R.H., “Thermal Performance of a Liquid Hydrogen Tank Multilayer Insulation System at Warm Boundary Temperatures of 630, 530 and 152 °R,” 27th Joint Propulsion Conference, AIAA-91-2400, June 1991.
3. Hasan, M.M., Lin, C.S., and Van Dresar, N.T., “Self-Pressurization of a Flightweight Liquid Hydrogen Storage Tank Subjected to Low Heat Flux,” NASA-TM-103804, July 1991.
4. Kassemi M, Kartuzova Olga. Effect of interfacial turbulence and accommodation coefficient on CFD predictions of pressurization and pressure control in the cryogenic storage tank. J Cryogenics 2016;74:138–53.
5. Mohammad Kassemi, Olga Kartuzova, Sonya Hylton, “ Validation of two-phase CFD models for propellant tank self-pressurization: Crossing fluid types, scales, and gravity levels,” Cryogenics, Volume 89, January 2018, Pages 1-15, 2018.
6. Linstrom P, Mallard W, Editors. NIST Chemistry WebBook, NIST Std. Ref. Database Number 69, NIST, 2005, http://webbook.nist.gov.
7. Menter, F. R., Kuntz, M., and Langtry, R., "Ten Years of Industrial Experience with the SST Turbulence Model," Turbulence, Heat and Mass Transfer 4, ed: K. Hanjalic, Y. Nagano, and M. Tummers, Begell House, Inc., 2003, pp. 625 - 632.
8. Egorov, Y., Boucker, M., Martin, A., Pigny, S., Scheuerer, M., and Willemsen, S., “Validation of CFD codes with PTS-relevant test cases,” 5th Euratom Framework Programme ECORA project, Vol. 2004, 2004, pp. 91–116.
9. Fan, W., and Anglart, H., “Progress in Phenomenological Modeling of Turbulence Damping around a Two-Phase Interface,” Fluids, Vol. 4, No. 3, 2019. https://doi.org/10.3390/fluids4030136, URL https://www.mdpi.com/2311-5521/4/3/136.